Dispersive readout scheme for a Josephson phase qubit

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We present experimental results on a dispersive scheme for reading out a Josephson phase qubit. A capacitively shunted dc-SQUID is used as a nonlinear resonator which is inductively coupled to the qubit. We detect the flux state of the qubit by measuring the amplitude and phase of a microwave pulse reflected from the SQUID resonator. By this low-dissipative method, we reduce the qubit state measurement time down to 25 μs, which is much faster than using the conventional readout performed by switching the SQUID to its non-zero dc voltage state. The demonstrated readout scheme allows for reading out multiple qubits using a single microwave line by employing frequency-division multiplexing.

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A vital ingredient of experiments on quantum bits is a detection tool to efficiently read out the state of a qubit. This detector must introduce as little back-action as possible, while showing a large measurement contrast; it should have negligible dissipation and offer fast operation. Superconducting quantum bits, such as the flux [1] and phase qubit [2], consist of superconducting loops interrupted by one or more Josephson junctions. Since their readable states can be discriminated by the magnetic flux passing through the qubit loop, it is common to use inductively coupled dc-SQUIDs as sensitive detectors.

The standard method to read out a Josephson phase qubit is to record the dc bias current at which the SQUID switches to its non-superconducting state [3–6]. This process generates heat directly on the chip and quasiparticles in the circuitry. Both effects are responsible for a relatively long cool-down time of about 1-2 ms that is required after each switching event. This, together with the time needed to ramp up the bias current of the SQUID, limits the repetition rate of the experiment.

For the flux qubit, non-destructive dispersive readout schemes have successfully been realized already some time ago, either by coupling to a high quality LC-tank circuit [7], or to a dc-SQUID [8]. So far, most measurements of phase qubits were typically done by the above mentioned switching current measurement of an inductively coupled dc-SQUID. Recently, first experiment overcoming the limitations of the switching readout was reported [9]. In this approach, the phase qubit was capacitively coupled to a transmission line which allows for direct probing its resonance frequency with a microwave pulse. This approach eliminates a readout dc-SQUID, but in turn introduce decoherence via the line coupled directly to the qubit.

In this letter, we present experiments on dispersive readout of a SQUID weakly coupled to a phase qubit. By using weak coupling between the SQUID and the qubit, this scheme protects the qubit from decoherence sources introduced by the readout circuitry. Moreover, while preserving the intrinsic coherence of the qubit, this method is suitable for reading out many qubits using a single microwave line and frequency-division multiplexing addressing individual readout SQUID resonators.

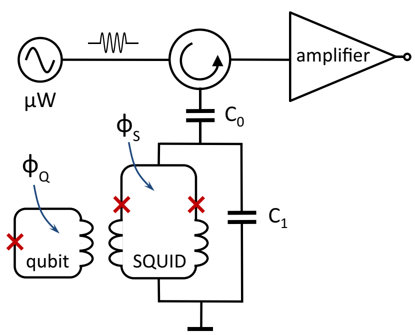

FIG. 1: (Color online) Scheme of the measurement setup. The SQUID with shunt capacitor C_1 coupled to the qubit. The pulsed microwave signal is applied via a cryogenic circulator, and the reflected signal is amplified by a cryogenic amplifier.

We couple the qubit to a capacitively shunted dc-SQUID which forms a tank circuit having a resonance frequency around 2 GHz. It is connected to a microwave line by a coupling capacitor C_0 shown in Fig. 1. Our sample was fabricated in a standard niobium-aluminium trilayer process. Measurement of the amplitude and phase of a reflected microwave pulse allows one to determine the shift of the resonance frequency of the SQUID-resonator and by doing this deduce the magnetic flux of the qubit state.

Depending on the applied microwave power, the SQUID resonator circuit can be operated in either linear or nonlinear regime. The nonlinear regime makes it possible using extremely sensitive bifurcation readout [10]. This may allow for a direct quantum non-demolition

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readout of a Josephson phase qubit, similar to what has already been realized for a flux qubit [11].

Figure 1 shows a simplified scheme of our measurement setting. At room temperature, the output of a continuous-wave microwave source is split using a power divider into reference and probe signals (not shown). The probe signal passes through a phase shifter and is amplitude-modulated by means of two mixers connected in series in order to achieve a large on-off ratio of about 64 dB. The pulsed signal is then attenuated in total by 70 dB using attenuators at several temperature stages of the dilution refrigerator. At the 30 mK stage, the signal is passed through a cryogenic circulator (Pamtech STE1438K) with isolation of 18 dB in the frequency range between 1.9 GHz and 2.4 GHz. From there, the signal is guided to the SQUID circuit by an on-chip coplanar transmission line.

The signal reflected from the sample goes back to the circulator towards a cold amplifier installed at the 4 K stage, specified to 42 dB gain at a noise temperature of 6 K (Quinstar QCA-S.3-30H). The narrow-band isolator together with a filter (Mini-Circuits VBFZ-2130) of pass band between 1.7 GHz and 2.4 GHz serve to protect the sample from the noise of the amplifier. At the output of the amplifier, a low-pass filter (Mini-Circuits VLF-3000) with a cut-off frequency of 3 GHz protects the amplifier and the whole system from high frequency noise. At room temperature, the signal is amplified by two amplifiers (Mini-Circuits ZX60-2534M) of total gain 76 dB and mixed together with the reference signal in an IQ mixer (Marki IQ1545LMP). The I and Q outputs of this mixer, which are determined by a combination of the phase and amplitude of the signal, are digitized by means of an 8-bit, 100 MS/s data acquisition card.

On chip, there are two magnetic flux lines, one for flux Φ_S biasing the SQUID, see Fig. 1, and another for flux Φ_Q biasing the qubit. The qubit is controlled by microwave pulses which are applied via a separate line (not shown) attenuated at several low temperature stages. The SQUID flux bias line is equipped with a current divider and filter at the 1 K stage, and a powder filter [12] at the sample holder. By taking the crosstalk of the two flux coils into account, we can independently change the flux that is seen by the qubit and the flux that is seen by the SQUID. This sample was designed with a large mutual inductance between qubit loop and dc-SQUID which allowed us to independently characterize the sample by the conventional switching-current technique. The dispersive readout results presented below were obtained without applying any dc-bias to the readout SQUID.

To operate the phase qubit, we biased it close to one flux quantum in its loop, giving rise to an asymmetric double-well potential [3]. The qubit quantum states are located in the shallow metastable well and can be distinguished by their tunneling rate to the neighboring deep well. In order to read out the qubit, this tunneling is triggered by applying a short (about 1 ns) flux pulse of small amplitude which tilts the potential such that tunneling occurs nearly exclusively only from the excited state. Since states in neighboring wells differ by the number of flux quanta in the loop, reading out the qubit is completed by measuring the resulting magnetic field via the inductively coupled dc-SQUID.

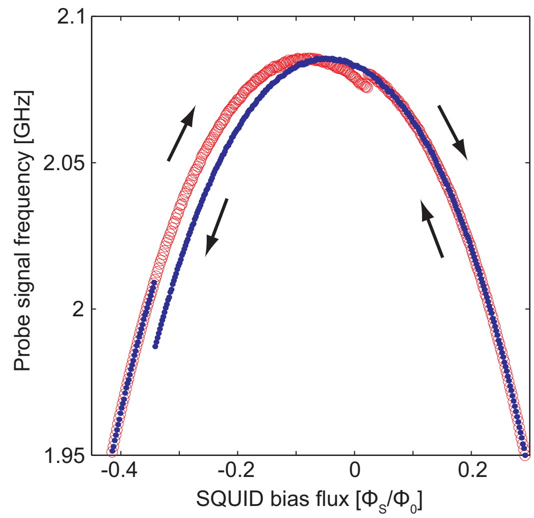

FIG. 2: (Color online) Microwave frequency applied to the SQUID vs. externally applied flux. The measurement points show the position of a dip in the reflected signal amplitude for two different directions of the flux sweep.

The the position of a dip in the amplitude of the reflected pulse is plotted in Fig. 2 as a function of microwave frequency and applied SQUID flux bias Φ_S. Data points indicate the dependence of the tank circuit resonance frequency on the applied bias flux. The larger (red) circles correspond to the flux swept from negative to positive values, while the smaller (blue) dots stand for the flux swept in opposite direction. During the flux sweep, due to the crosstalk between Φ_S and Φ_Q flux lines approximately one flux quantum Φ_0 enters or leaves the qubit loop, which gives rise to abrupt shift of the dip frequency at specific flux bias values. The resonance frequency shift at a bias flux of -0.35 Φ_0 is about 22 MHz, which is larger than the tank circuit's resonance line width of about 4 MHz. This scheme is thus capable of single-shot detection of the qubit flux state.

The SQUID resonator frequency shift induced by the qubit is shown in detail in Fig. 3(a). It displays two traces of the normalized reflected signal amplitude versus the applied microwave frequency in the vicinity of the qubit-state switching. Here, the resonance was located at around 1.9 GHz where the SQUID has higher sensitivity to the flux. The amplitude of the reflected signal drops at the resonance frequency. For this measurement, very low microwave power of -120 dBm was applied to SQUID to stay in the linear regime, giving rise to the Lorentzian shape of the resonance dips. Taking into account the line width of 4 MHz and the dependence of the resonance frequency on the flux, we achieve a flux

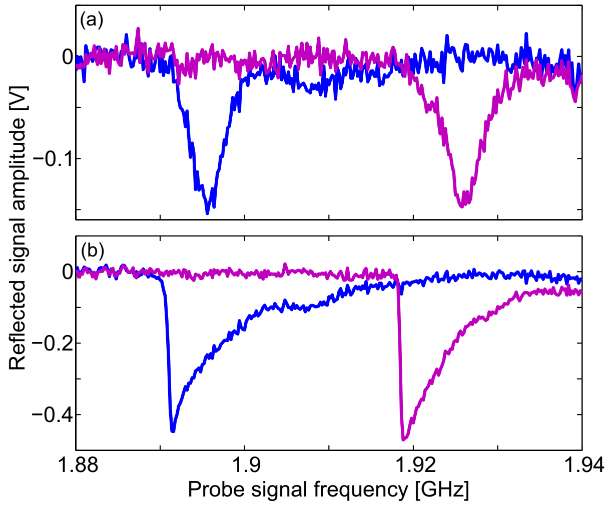

FIG. 3: (Color online) Shift of the resonance frequency of the SQUID resonator by 30 MHz due to the qubit changing its magnetic flux by approximately Φ_0. (a) In the linear regime. (b) SQUID driven in the non-linear regime. Note the larger signal amplitude compared to the linear regime.

resolution of 2-3 mΦ_0 of the detector at operating frequency of 1.9 GHz. As the two qubit states differ by magnetic flux of the order of Φ_0, this allows for a very weak inductive coupling between SQUID and qubit for future experiments. Fig. 3 (b) shows the same frequency range as above, but now the power of the input signal is larger, -115 dBm, driving the SQUID into the nonlinear regime. This is revealed by the shape of the dips. The advantage of the non-linear regime is the sharper edge on the low frequency side which allows for an even better flux resolution of about 0.5-0.7 mΦ_0.

Figure 4 shows Rabi oscillations of the qubit measured for different driving powers of the qubit microwave driving. As it is expected, the frequency of Rabi oscillations increases approximately linearly with the driving field amplitude. The measured energy relaxation time of the tested qubit is rather short and is of order of $T_1 = 5$ ns. This time is it not limited by the chosen type of readout but rather determined by the intrinsic coherence of the qubit itself. We verified this fact by measuring the same qubit with the conventional SQUID switching current method, which yielded very similar T_1. The observed short coherence time is likely to be caused by the dielectric loss in the silicon oxide forming the insulating dielectric layer around the qubit Josephson junction [6].

In conclusion, we have demonstrated a dispersive readout scheme for a Josephson phase qubit. This scheme avoids the switching of the SQUID flux detector into a resistive state. Due to much lower dissipation in the circuit, we we can reduce SQUID measurement time down to 25 μs without observing any noticeable heating effects. This readout repetition time is about 40 times shorter than the time typically achieved with the conventional readout. In our setup, the shortest repetition time is limited by the amplifiers for the I and Q signals and could be further reduced down to the 10 - 100 nanosecond range by expanding the band of these amplifiers, as it has been already demonstrated for flux qubits [11]. This short measurement time and the possibility of using frequency-division multiplexing readout [13] make our approach promising for future experiments scaled up to multiple phase qubits.

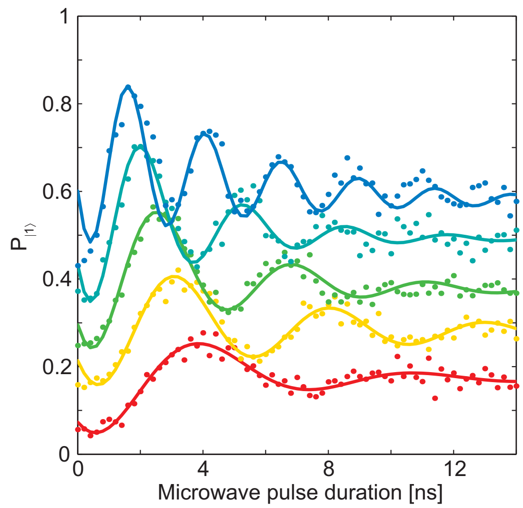

FIG. 4: (Color online) Coherent oscillations of the qubit for different driving powers, from bottom to top: -18 dBm, -15 dBm, -12 dBm, -9 dBm and -6 dBm. Curves are offset by 0.1 for better visibility.

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